Service Path Attribution Networks (SPANs): A Network Flow Approach to Ecosystem Service Assessment

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ABSTRACT

Ecosystem services are the effects on human well-being of the flow of benefits from ecosystems to people over given extents of space and time. The Service Path Attribution Network (SPAN) model provides a spatial framework for determining the topology and strength of these flows and identifies the human and ecological features which give rise to them. As an aid to decision-making, this approach discovers dependencies between provision and usage endpoints, spatial competition among users for scarce resources, and areas of highest likely impact on ecosystem service flows. Particularly novel is the model’s ability to quantify services provided by the absence of a flow. SPAN models have been developed for a number of services (scenic views, proximity to open space, carbon sequestration, flood mitigation, nutrient cycling, and avoided sedimentation/deposition), which vary in scale of effect, mechanism of provision and use, and type of flow. Results using real world data are shown for the US Puget Sound region.

Keywords: Ecosystem Service Assessment, Environmental Planning, Flow Criticality, Flow Density, Flow Modeling, Network Flow, Service Flows, Service Path Attribution Network (SPAN), Spatial Decision Making

INTRODUCTION

The concept of Ecosystem Services (ES) provides a cohesive scientific view of the many mechanisms through which nature contributes to human well-being (Daily, 1997). From the more well-known services, such as the provision of food, clean water, medicine, and raw materials to the more ephemeral services of natural systems regulation, aesthetics, and cultural preservation, ecosystem services both directly and indirectly impact the quality of life of people around the globe (Daily, 1997; National Research Council (NRC), 2005; Millennium Ecosystem Assessment (MA), 2005).
Ecosystem service assessment, as an application of ecological and economic principles, is the task of quantifying the values conferred by natural systems to their human counterparts for the purpose of improving spatial decision making around land management. Focusing on both the biophysical mechanisms of ES provision and the economic implications of ES use can allow our societies to balance the sides of the “nature vs. economy” equation, leading ultimately to better management and governance (Millennium Ecosystem Assessment (MA), 2005).

Since analyzing ecosystem services requires modeling coupled human-natural systems, an ongoing hurdle in this field is properly combining techniques from both socio-economics and the physical sciences so as to capture both sides of the service dynamics. However, these fields often make use of quite different modeling techniques, underlying assumptions, and spatio-temporal scales. Furthermore, even with an optimal integration of modeling techniques, many of the interactions between humans and their environments remain clouded by uncertainty or completely unknown to science (Limburg, O’Neill, Costanza, & Farber, 2002).

For these reasons, concrete techniques for supporting quantification, spatial mapping and economic valuation of ES have lagged behind the popularity of the concept, making it difficult to productively use ES as a basis for scientific investigation and accurate decision-making (Boyd & Banzhaf, 2007; Wallace, 2007). Virtually all methodologies employed or proposed (Costanza et al., 1997a; Farber et al., 2006; Nelson et al., 2009; Tallis & Polasky, 2009) to quantify ES and their values convert proxy categorical information, chiefly land cover type, into coarse assessments of value or potential provision through the use of aggregated coefficients. Such approaches ignore the complex, multi-scale dynamics of ES provision, use, and flow, and are insufficiently precise to enable detailed scenario analyses or inform spatial planning decisions. Current approaches tend to address the following four points unsatisfactorily:

1. **Scalability:** Ecosystem services are provided and used at a wide variety of spatial and temporal scales (Hein, van Koppen, de Groot, & van Ierland, 2006; Fisher & Turner, 2008). However, most current spatial ES models are calibrated to operate on one fixed scale. A more robust model would be able to adapt its scale and associated complexity to match each problem and have some means of automated or semi-automated recalibration in conjunction with these scale changes.

2. **Generalizability:** When different ES models are developed using entirely independent assumptions and abstractions, comparison of their results for the purpose of decision-making, particularly around tradeoff analysis, becomes very difficult. The development of a unified framework for quantifying many different ecosystem services with the same (or comparable) parameters is sorely lacking but has the potential to make ES assessment a much more useful tool in spatial decision-making contexts.

3. **Benefit-Centrism:** Although earth system simulation modeling is a well established field, especially with respect to climate and hydrologic modeling, such models focus largely or exclusively on describing and predicting how physical environmental systems behave under varying conditions. In order to describe ecosystem services, the effects of the environmental system on the human economic system (and vice versa) should be central to the model rather than an addendum to a separate analysis (Boyd & Banzhaf, 2007; Wallace, 2007; Bagstad, Johnson, Villa, Krivov, & Ceroni, 2012).

4. **Communicating Uncertainty:** The results of many earth system simulation or process-based models are deterministic values for their component variables. Since all modeling manipulates and produces uncertainty and the number of unknowns is perhaps greater in ES modeling than in many other disciplines, special care should be taken to preserve the sources of this
uncertainty and convey them in the model outputs. Being explicit in this way is doubly useful for decision support systems since it increases the users’ trust in the tool and enables more informed planning on their part (Kinzig et al., 2003).

This contribution addresses these issues through a combination of network flow, image analysis, parallelism, and agent-based techniques. The end result is a model which emphasizes service flows rather than their in situ production, reflecting the definition of ecosystem services given in Villa, Ceroni, Bagstad, Johnson, and Krivov (2009): “the effects on human well-being of the flow of benefits from an ecosystem endpoint to a human endpoint over given extents of space and time.” This model, called the Service Path Attribution Network (SPAN), provides a spatial framework for determining the topology and strength of these flows and identifies the human and ecological features which give rise to them. As an aid to decision-making, this approach discovers dependencies between provision and usage endpoints, spatial competition among users for scarce resources, and areas of highest likely impact on ecosystem service flows. Particularly novel is the model’s ability to quantify services provided by the absence of a flow.

SPAN models have been developed for a number of services (scenic views, proximity to open space, carbon sequestration, flood mitigation, nutrient cycling, and avoided sedimentation/deposition), which vary in scale of effect, mechanism of provision and use, and type of flow. Due to page limitations, we concentrate on results obtained using real world data for the scenic view service in the US Puget Sound region. Results for other services will be made available online and in forthcoming publications (Bagstad et al., 2012).

**STRUCTURE OF THE MODEL**

In the SPAN framework, each ecosystem service is defined in terms of the flow of some form of matter, energy, or information, known as the *service medium*, from an ecosystem source to a human user. An ecosystem can be credited with providing a service in one of two cases:

1. If the medium is considered beneficial to people (e.g., food, drinking water, or scenic views), then the service is realized by the creation and delivery of this medium. We refer to this class of ecosystem services as *provisioning services*.
2. If the medium is considered detrimental to quality of life (e.g., flood water, unwanted sediment or nutrients, disease, or wildfire), then an ecosystem may provide the service by preventing its flow to vulnerable human groups. We refer to this class of ecosystem services as *preventive services*.

Thus for some ecosystem services, accumulation of the medium by beneficiaries provides economic value, while for other services, the value is generated by preventing this accumulation.

**Mapping from Geospace to Vertices**

Since the calculations described above will be performed on a flow network, the first step after determining the service medium is to map the spatial region under study onto a directed acyclic graph that represents the topology of those geographic areas that participate in the production, use, transport, or absorption of the given service medium. Each spatial region is represented by a vertex in the graph, along with its underlying feature measurements. Each boundary element between adjacent regions is represented by a directed edge indicating the direction of service flow (Figure 1).

Because the complexity of the flow analysis is driven by the number of edges in the network, an initial step in building a SPAN is selecting the study scale and discretizing the overall region of interest into a set of spatially disjoint locations according to the particular service’s production, use, and flow character-
istics. Given the underlying georeferenced data set, this spatial segmentation process may be automated via techniques from image analysis, computer vision, or spatial data mining, or may even be manually supplied using a predetermined partitioning, such as a map of geopolitical or bioregional boundaries.

Although many natural processes are often approximated by continuous models (e.g., hydrologic or atmospheric dynamics), we believe a discrete paradigm offers several advantages. First, environmental datasets are almost always comprised of discretely-sampled measurements. These usually come in the form of either polygon maps or regular grids with associated feature values at each measured location. Using discrete regions in the SPAN model allows us to match our algorithms to the same scale and representation as that of the underlying data. The second advantage is that agent-based algorithms can be readily applied to the data to identify flow pathways between service providers and beneficiaries. A third and final advantage is that the computational complexity of some models can be reduced by aggregating high resolution data within each region into simpler representations, such as probability distributions or functional approximations, which the agent system may then use as input. A caveat to this is that acceptable scales for downsampling must be fine enough to accurately represent the movement of the given service and are thus constrained by its flow properties.

Service Carriers

In the network, the service medium is reified as a collection of service carrier agents, represented as 5-tuples \((A,P,R,Q,X)\) with the following meanings:

- **Actual Weight** \(A\): A numeric (or otherwise quantifiable) representation of the quantity or quality of the service medium that a service carrier is transporting through the network.
- **Possible Weight** \(P\): The amount of the service medium that could be transported by this service carrier if all upstream sink effects were nullified. \(P - A\) is the sunk service weight, which is of particular relevance when assessing preventive service flows.
- **Route** \(R\): A list of the vertices \((v_1, v_2, \ldots, v_N)\), through which this service carrier has traveled, inclusive of the vertex in which the carrier is currently located. The current vertex can be addressed as \(\text{Last}(R)\). Similarly, the first vertex in the route can be addressed as \(\text{First}(R)\). \(\text{Subroute}(R, v)\) is the list of all vertices in the segment of route \(R\) which begins at \(v\) and ends with \(\text{Last}(R)\).
- **Sink Effects** \(Q\): A map of the vertices in \(K\) encountered along the route \(R\) to the amount of the service medium which they absorb from this carrier during the simulation. If this amount is 0, no entry for this vertex will be added to \(Q\). Finally, if \(Q(k)\) is undefined, its value should be considered 0.

Figure 1. Pixelated landscape segmented into regions by underlying feature measurements. Each region corresponds to a vertex in the SPAN, and the arrows depict the direction of service flow between regions. \(A\) and \(F\) are source regions, \(B\) is a service sink, and regions \(C, E,\) and \(H\) contain potential service users, denoted by an asterisk on the region’s label.
• **Use Effects** \( X \): A map of the vertices in \( U \) encountered along the route \( R \) to the amount of the service medium which they absorb from this carrier during the simulation. If this amount is 0, no entry for this vertex will be added to \( X \). Finally, if \( X(u) \) is undefined, its value should be considered 0.

The movement of these carriers through the SPAN is then specified by three parameters:

1. **Movement Function**, \( \text{Move}: (A,P,R,Q,X) \rightarrow ((A,P,R,Q,X)^*) \): This function maps a carrier \((A_0,P_0,R_0,Q_0,X_0)\) to a list of new carriers \(((A_1,P_1,R_1,Q_1,X_1), (A_2,P_2,R_2,Q_2,X_2), ..., (A_N,P_N,R_N,Q_N,X_N))\), where \( N \) is the number of outgoing edges from Last \((R_0)\). These represent the next steps of the service carrier through the SPAN. Each new carrier route is formed by appending one of the vertices reachable by an outgoing edge from Last \((R_0)\) onto \((R_0)\). All vertices directly reachable by an outgoing edge are represented without repetition. The weights associated with these routes describe the amount of the service medium which follows each particular route away from Last \((R_0)\), including any effects due to route branching. If a carrier moves into a vertex with no outgoing edges, then \( \text{Move} (A,P,R,Q,X) \) evaluates to an empty list.

2. **Decay Function**, \( \text{Decay}: (W,R) \rightarrow W' \): Some service media may decay in quality or importance as a function of the distance they travel or by some limiting effect of the route they follow. For example, the view of a mountain becomes less impressive the further away it is. We represent this in the SPAN by a function that maps a weight \( W \in \{A,P\} \) and its associated route \( R \) to a new weight \( W' \leq W \) which is the remaining weight after applying the decay effects along this route. In order to reverse this calculation (required to calculate Possible and Actual Flow values in the section entitled *Analyzing the Carrier Caches*), a corresponding function \( \text{Undecay}: (W',R) \rightarrow W \) must also be supplied.

3. **Transition Threshold**, \( \theta_{\text{trans}} \): This is the minimum possible weight \( P \) that any carrier in the network must have in order to be a candidate for the Movement function. If \( P \) ever becomes less than \( \theta_{\text{trans}} \), the carrier expires and the medium it bears ceases to propagate any further. Increasing this parameter will decrease the maximum route length for carriers.

**Location Properties**

With the study area partitioned and the service medium identified, each vertex \( v \) in the SPAN is assigned eight properties (Table 1), which describe its region’s effects on the service medium. Those properties labeled *Absolute* are expressed in physical units. Those labeled *Relative* are represented with a unitless value from [0,1]. Both absolute and relative values may be expressed deterministically or as probability distributions to better account for uncertainty in the feature data and the location property functions. The properties that saturate represent limited absorption or usage capacities. Regions with these values will not absorb or use quantities of the service medium greater than these limits during the flow simulation. Conversely, the non-saturating properties represent amounts of absorption or usage that are entirely dependent on the amount of the service medium encountered.

For many but not all ecosystem services, either the absolute or the relative forms of the source, sink, use, and disuse functions are defined. In general, cultural and aesthetic services (e.g., scenic views, proximity to open space, or preservation of a cultural icon) are most easily modeled using relative source, sink, and use values. Absolute values are better suited to represent services based on the movement of matter or energy across landscapes (e.g., water provision, flood mitigation, or carbon sequestration). In this case, the absolute source value of a region represents the amount of the medium (e.g., runoff or carbon sequestration— including avoided release of stored carbon) that it produces during the simulation.
Since the SPAN model currently operates either statically in time or on an event-based timescale, this source value will be based on a predefined time window or a particular event, such as a 100-year storm.

While the source and sink values represent the landscape’s production and absorption capacities, the use and disuse values attempt to capture the human component of this system. They should be interpreted as follows:

- For a provisioning service, a region’s disuse value denotes the amount of the service medium which cannot be used by the beneficiaries within its bounds, stated in either physical units or as a fraction of the total quantity encountered. The use value indicates the total that can be captured by beneficiaries. These may be used to represent both institutional constraints as well as physical or technological limitations on the extraction process.
- For a preventive service, the disuse value should be interpreted as a limit on the amount of the service medium encountered which will not cause any measurable damage to the beneficiaries in a region. The use value then represents the amount beyond which no further damage is caused (generally because all assets of note have already been ruined).

A final property of service usage is that it may be either destructive or non-destructive on the service medium. This is correlated with the rivalry of the resource being analyzed. For example, with water provision, the extraction and use of water is clearly rival and destructive of the resource since collecting it in one region prevents its use by all downstream regions. The same applies to carbon sequestration, as a finite quantity of carbon sequestration capacity must be shared among all users in order to maintain the atmospheric carbon balance at a safe level. However, in the case of flood mitigation, the same water that causes flood damage in one region may cause further damage in others. Thus, by providing the service of flood mitigation to one area, many areas may simultaneously receive the same benefit depending on their spatial configuration. The same non-rivalness may often hold for the informational or accessibility-based services. For example, the availability of scenic views may benefit many users in different regions without competition for this resource.

### Property Thresholds

As a means of restricting service flow calculations to parts of the system deemed more important than others, a positive, real-valued threshold may be associated with each of the

*Table 1. Location properties assigned to each vertex in the SPAN*

<table>
<thead>
<tr>
<th>Location Property</th>
<th>Function</th>
<th>Saturating?</th>
<th>Relationship to Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Source</td>
<td>Source_{abs}(v)</td>
<td>N/A</td>
<td>Amount produced in physical units</td>
</tr>
<tr>
<td>Absolute Sink</td>
<td>Sink_{abs}(v)</td>
<td>Yes</td>
<td>Amount potentially absorbed</td>
</tr>
<tr>
<td>Absolute Use</td>
<td>Use_{abs}(v)</td>
<td>Yes</td>
<td>Amount potentially usable</td>
</tr>
<tr>
<td>Absolute Disuse</td>
<td>Disuse_{abs}(v)</td>
<td>Yes</td>
<td>Amount potentially unusable</td>
</tr>
<tr>
<td>Relative Source</td>
<td>Source_{rel}(v)</td>
<td>N/A</td>
<td>Amount produced in relative rankings</td>
</tr>
<tr>
<td>Relative Sink</td>
<td>Sink_{rel}(v)</td>
<td>No</td>
<td>Amount potentially absorbed</td>
</tr>
<tr>
<td>Relative Use</td>
<td>Use_{rel}(v)</td>
<td>No</td>
<td>Amount potentially usable</td>
</tr>
<tr>
<td>Relative Disuse</td>
<td>Disuse_{rel}(v)</td>
<td>No</td>
<td>Amount potentially unusable</td>
</tr>
</tbody>
</table>
above location properties. These shall be labeled as follows:

\[ \theta^m, \text{ where, } m \in \{\text{abs, rel}\}, t \in \{\text{source, sink, use}\}. \]

These thresholds will be used to determine the vertex sets \( S, K, \) and \( U \) in the following section.

**The Graph Specification**

Now that the mapping from geospace to vertices has been detailed and all the necessary terminology introduced, we can present the graph specification of our SPAN model in detail. A SPAN is built on a directed acyclic graph \( G=(V,E) \), possessing the following six properties:

1. Every vertex \( v \in V \) represents a single geospatial area, whose polygon-bounded region is distinct and does not overlap topologically with that of any other vertex \( v' \in V \).
2. Every directed edge \( (u,v) \in E \) represents a path along which a service carrier may travel from location \( u \) to location \( v \). This path may represent an adjacency relationship (shared boundary) between \( u \) and \( v \) in the georeferenced space, but it may also connect two spatially separated locations in the event that the service medium’s flow may be better modeled in such a manner. For example, two cities which are accessible along the same train line may be connected by an edge in the SPAN for services which may travel along human transportation networks.
3. A subset \( S \subseteq V \) contains those vertices which we shall call *service sources*. For each \( s \in S \), either \( \text{Source}^\text{abs}(s) \geq \theta^\text{source}^\text{abs} \text{ or } \text{Source}^\text{rel}(s) \geq \theta^\text{source}^\text{rel} \), depending on whether the source is absolute or relative.
4. A subset \( K \subseteq V \) contains those vertices which we shall call *service sinks*. For each \( k \in K \), \( \text{Sink}^\text{abs}(k) \geq \theta^\text{sink}^\text{abs} \text{ or } \text{Sink}^\text{rel}(k) \geq \theta^\text{sink}^\text{rel} \), depending on whether the sink is absolute or relative.
5. A subset \( U \subseteq V \) contains those vertices which we shall call *service users*. For each \( u \in U \), \( \text{Use}^\text{abs}(u) \geq \theta^\text{use}^\text{abs} \text{ or } \text{Use}^\text{rel}(u) \geq \theta^\text{use}^\text{rel} \), depending on whether the use is absolute or relative.
6. \( S, K, \) and \( U \) need not be disjoint.

This completes the description of the SPAN model’s structure, parameterization, and correspondence to the underlying spatial data. Next, we must connect the regions providing services with their beneficiaries.

**FLOW ANALYSIS**

Thus far, the ecosystem service properties of our study area have been determined within each region without regard for the relationships between regions. We call these values the *theoretical* source, sink, and use estimates of our service assessment because without determining where the service medium generated at the sources will flow, we cannot determine which users, if any, will receive its benefits or which sinks will actually impede its movement. This highlights an important aspect of the SPAN model’s definition of service provision: unless the generated benefit is actually made accessible to human beneficiaries, no service is attributed to the ecosystem. Furthermore, since services can flow to beneficiaries from different sources, it is important to correctly assign value to sources that are actually used.

The algorithm that determines these spatial relationships consists of three phases: Initializing the Carrier Network, Discovering the Flow Topology, and Analyzing the Carrier Caches.

**Initializing the Carrier Network**

First, each vertex \( v \in U \) in the SPAN graph is assigned an empty set, called its *carrier cache* \( \text{Cache}(v) \). A service carrier is initialized in each source set \( s \in S \) with its weights \( A \) and \( P \) both set to either \( \text{Source}^\text{abs}(s) \) or \( \text{Source}^\text{rel}(s) \), depending on the service medium. Its route \( R \) is the singleton list \( (s) \), and the sink and use effects values \( Q \) and \( X \) are empty maps \( \{\emptyset \rightarrow \emptyset\} \).
If the service medium is relative, each carrier becomes the root node of a depth-first tree traversal in which Move \((A,P,R,Q,X)\) is used as the successor function at each step. Because the sink and use values do not saturate, their effects on carrier weights are invariant of the order in which they are encountered. This means that all carrier tree traversals may be performed in any order or in parallel if the computational capacity is available.

If the service medium is absolute, then sink and use values do saturate. Therefore, the order of the computation is quite important. In this case, the flow analysis can be performed via a breadth-first tree traversal, in which the starting open list is comprised of all the root node service carriers.

**Discovering the Flow Topology**

Let us refer to the open list in a carrier tree traversal as \(O\) and the set of all carriers in \(O\) for which \(\text{Last}(R)=v\) be \(\text{Carriers}(O,v)\). At each step of the traversal, each of the carriers in \(O\) will have its actual and possible weights \(A\) and \(P\) decreased by the sink and rival use effects of its current location in different ways. To

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**Box 1.**

\[
\begin{align*}
\text{Inflow}_{\text{actual}}(O,v) &= \begin{cases} 
\sum_{(A,P,R,Q,X)\in \text{Carriers}(O,v)} A, & \text{if } |\text{Carriers}(O,v)| > 0 \\
1, & \text{otherwise}
\end{cases} \\
A_{\text{contrib}}(O,a,v) &= \frac{a}{\text{Inflow}_{\text{actual}}(O,v)} \\
A_{\text{sunk}}(O,a,v) &= \begin{cases} 
\min (a, \text{Sink}_{\text{rel}}(v)), & \text{if } \text{Sink}_{\text{rel}}(v) > 0 \\
\min (a, A_{\text{contrib}}(O,a,v) \times \text{Sink}_{\text{abs}}(v)), & \text{otherwise}
\end{cases} \\
A_{\text{ignored}}(O,a,v) &= \begin{cases} 
\min (a - A_{\text{sunk}}(O,a,v), \text{Disuse}_{\text{rel}}(v)), & \text{if } \text{Use}_{\text{rel}}(v) > 0 \\
\min (a - A_{\text{sunk}}(O,a,v)), & \text{otherwise}
\end{cases} \\
A_{\text{used}}(O,a,v) &= \begin{cases} 
\min (a - A_{\text{sunk}}(O,a,v) - A_{\text{ignored}}(O,a,v), \text{Use}_{\text{rel}}(v)), & \text{if } \text{Use}_{\text{rel}}(v) > 0 \\
\min (a - A_{\text{sunk}}(O,a,v) - A_{\text{ignored}}(O,a,v) - A_{\text{contrib}}(O,a,v) \times \text{Use}_{\text{abs}}(v)), & \text{otherwise}
\end{cases} \\
W_{\text{sunk}}(O,v) &= \sum_{(A,P,R,Q,X)\in \text{Carriers}(O,v)} A_{\text{sunk}}(O,A,v) \\
W_{\text{ignored}}(O,v) &= \sum_{(A,P,R,Q,X)\in \text{Carriers}(O,v)} A_{\text{ignored}}(O,A,v) \\
W_{\text{used}}(O,v) &= \sum_{(A,P,R,Q,X)\in \text{Carriers}(O,v)} A_{\text{used}}(O,A,v)
\end{align*}
\]
describe this, we first establish the following definitions (see Box 1).

For each carrier \((A, P, R, Q, X) \in \text{Carriers}(O, v)\) \(\forall v \in V\), if the service medium is non-rival, let \(A' = A - A_{\text{sunk}}(O, A, v)\) and \(P' = P\). Otherwise, let \(A' = A - A_{\text{sunk}}(O, A, v) - A_{\text{used}}(O, A, v)\) and \(P' = P - A_{\text{used}}(O, A, v)\). If \(A_{\text{sunk}}(O, A, v) > 0\), let \(Q'\) be the map \(Q\) with the additional entry \(v \rightarrow A_{\text{sunk}}(O, A, v)\). If \(A_{\text{used}}(O, A, v) > 0\), store a new carrier \((\text{Decay}(A'), R, \text{Decay}(P'), R, Q', X)\) in \(\text{Cache}(v)\). If \(A_{\text{sunk}}(O, A, v) > 0\) and the service medium is rival, let \(X'\) be the map \(X\) with the additional entry \(v \rightarrow A_{\text{sunk}}(O, A, v)\). If \(\text{Decay}(P', R) \geq \theta_{\text{trans}}\), add the carriers created by \(\text{Move}(A', P', R, Q', X')\) to the open list \(O\). In all cases, remove \((A, P, R, Q, X)\) from \(O\).

Next, we decrement the sink, use, and disuse values associated with location \(v\) prior to the next round of computations. If the service medium is absolute, let \(\text{Sink}_{\text{abs}}(v) = \text{Sink}_{\text{abs}}(v) - W_{\text{sunk}}(O, v)\), \(\text{Use}_{\text{abs}}(v) = \text{Use}_{\text{abs}}(v) - W_{\text{used}}(O, v)\), and \(\text{Disuse}_{\text{abs}}(v) = \text{Disuse}_{\text{abs}}(v) - W_{\text{ignored}}(O, v)\).

Once all the child carriers have been added to the open list, we can continue our traversal in either a breadth-first or depth-first manner as dictated. The recursion ends when all the leaf nodes of the carrier tree have been explored.

**Analyzing the Carrier Caches**

Once the flow model has completed execution, each carrier cache \(\text{Cache}(v)\) should now contain a service carrier for each flow path which leads to it from any ecosystem source location on the landscape. These carriers can now be analyzed to determine the total amount of service each location receives from each producer, which sinks and rival use effects block downstream access to the service medium, and what parts of the landscape exhibit the greatest flow density. All of these calculations are possible because each carrier contains not only its actual and possible weights and the sink effects encountered during the simulation but also the complete flow path topology.

The results of this path analysis are several.

1. **Theoretical Source, Sink, Use**: The names given to the in situ location properties of each site determined prior to flow analysis (possibly multiplied by a scaling term) as described in the Location Properties section (see Box 2 for equations).
2. **Possible Source, Use, Flow**: Estimates of the fraction of the source’s service medium which is reachable by users along the flow paths, the amount that each use location receives along the flow paths, and the flow

"Box 2."

\[
\begin{align*}
\text{Source}_{\text{theoretical}}(v) & = \begin{cases} 
\text{Source}_{\text{rel}}(v) \times |U|, & \text{if service medium is relative} \\
\text{Source}_{\text{abs}}(v), & \text{otherwise}
\end{cases} \\
\text{Sink}_{\text{theoretical}}(v) & = \begin{cases} 
\text{Sink}_{\text{rel}}(v) \times |S| \times |U|, & \text{if service medium is relative} \\
\text{Sink}_{\text{abs}}(v), & \text{otherwise}
\end{cases} \\
\text{Use}_{\text{theoretical}}(v) & = \begin{cases} 
\text{Use}_{\text{rel}}(v) \times \frac{\sum_{s \in S} \text{Source}_{\text{rel}}(s)}{|U|}, & \text{if service medium is relative} \\
\text{Use}_{\text{abs}}(v), & \text{otherwise}
\end{cases}
\end{align*}
\]
density through each region in the study area. These values are aggregates of the service carriers’ possible flow $P$ values, so they disregard the effects of sink locations upstream of each region. This provides an upper bound for the landscape’s service flow potential if development scenarios are implemented which minimize these effects (see Box 3 for equations).

3. **Actual Source, Sink, Use, Flow**: These are the same as their Possible equivalents, except that they aggregate the service carriers’ actual flow $A$ values, thereby including sink effects in their calculations. Actual Sink is the aggregate of all sink effects $Q$ contained in all cached service carriers. This provides a snapshot of the actual state of ecosystem service flows in the region (see Box 4 for equations).

4. **Inaccessible Source, Sink, Use**: The difference between Theoretical and Possible values for Source and Use. The difference between Theoretical and Actual values for Sink. These represent unreachable source production, unutilized sinks, and unsaturated use capacity due to flow topology (see Box 5 for Equations).

5. **Blocked Source, Use, Flow**: The difference between Possible and Actual values. Unreachable source production, unsaturated use capacity, and lost flow density due to sink effects (see Box 6 for equations).

For provisioning services, the use values calculated in this stage represent met (or unmet) user demand, sinks are considered detrimental, and source regions are valued according to the quantity of the service medium they produce which is received by human beneficiaries. Because receipt of the service medium is desirable, the landscape features which facilitate its transport through intermediate regions are also of value.

For preventive services, greater use indicates greater damage incurred due to encounters with the service medium. Regions with high source estimates or flow densities are undesirable as they represent the presence of a threat. Because they impede the movement of this threat, sinks along flow paths become the providers of value to human beneficiaries.

---

**Box 3.**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Source_{possible}(v) = \sum_{u \in U} \sum_{(A,P,R,Q,X) \in \text{Cache}(u)} P_{\text{First}(R)=v}$</td>
<td>Source of possible values</td>
</tr>
<tr>
<td>$Use_{possible}(v) = \sum_{(A,P,R,Q,X) \in \text{Cache}(v)} P$</td>
<td>Use of possible values</td>
</tr>
<tr>
<td>$Loss_{possible}(R, X, v) = \sum_{v' \in \text{Subroute}(R,v)} X(v')$</td>
<td>Loss of possible values</td>
</tr>
<tr>
<td>$Flow^{\text{contrib}}<em>{possible}(P, R, X, v) = \begin{cases} \text{Undecay}(P + Loss</em>{possible}(R, X, v)), &amp; \text{if }</td>
<td>\text{Subroute}(R, v)</td>
</tr>
<tr>
<td>$Flow_{possible}(v) = \sum_{u \in U} \sum_{(A,P,R,Q,X) \in \text{Cache}(u)} Flow^{\text{contrib}}_{possible}(P, R, X, v)$</td>
<td>Total flow possible</td>
</tr>
</tbody>
</table>

---

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Box 4.

\[
\begin{align*}
\text{Source}_{\text{actual}}(v) &= \sum_{u \in U} \sum_{(A,P,R,Q,X) \in \text{Cache}(u)} A_{\text{First}(R)=v} \\
\text{Sink}_{\text{actual}}(v) &= \sum_{u \in U} \sum_{(A,P,R,Q,X) \in \text{Cache}(u)} Q(v) \\
\text{Use}_{\text{actual}}(v) &= \sum_{(A,P,R,Q,X) \in \text{Cache}(v)} A \\
\text{Loss}_{\text{actual}}(R, Q, X, v) &= \sum_{v' \in \text{Subroute}(R,v)} Q(v') + X(v') \\
\text{Flow}_{\text{actual}}^{\text{contribution}}(A, R, Q, X, v) &= \begin{cases} 
\text{Undecay} (A + \text{Loss}_{\text{actual}}(R, Q, X, v)) , & \text{if } |\text{Subroute}(R,v)| > 0 \\
0 , & \text{otherwise}
\end{cases} \\
\text{Flow}_{\text{actual}}(v) &= \sum_{u \in U} \sum_{(A,P,R,Q,X) \in \text{Cache}(u)} \text{Flow}_{\text{actual}}^{\text{contribution}}(A, R, Q, X, v)
\end{align*}
\]

Box 5.

\[
\begin{align*}
\text{Source}_{\text{inaccessible}}(v) &= \text{Source}_{\text{theoretical}}(v) - \text{Source}_{\text{possible}}(v) \\
\text{Sink}_{\text{inaccessible}}(v) &= \text{Sink}_{\text{theoretical}}(v) - \text{Sink}_{\text{actual}}(v) \\
\text{Use}_{\text{inaccessible}}(v) &= \text{Use}_{\text{theoretical}}(v) - \text{Use}_{\text{possible}}(v)
\end{align*}
\]

Box 6.

\[
\begin{align*}
\text{Source}_{\text{blocked}}(v) &= \text{Source}_{\text{possible}}(v) - \text{Source}_{\text{actual}}(v) \\
\text{Use}_{\text{blocked}}(v) &= \text{Use}_{\text{possible}}(v) - \text{Use}_{\text{actual}}(v) \\
\text{Flow}_{\text{blocked}}(v) &= \text{Flow}_{\text{possible}}(v) - \text{Flow}_{\text{actual}}(v)
\end{align*}
\]
Decision Making with SPAN Results

This information, in combination with maps of the flow topology and density, can be used to target spatial planning decisions that intend to change or preserve service flows as well as to estimate the comparative effects of different development actions on a region’s ecosystem services profile.

Some policy options illuminated by these results include:

- Managing landscapes to create greater Source values.
- Modifying human systems to increase their ability to extract and use the Service Medium which flows to them.
- Increasing flow capacity along routes to users by decreasing the effects of Sinks along these paths (landscape management).
- Increasing flow capacity along routes to users by regulating upstream Destructive Use of the service medium (institutional).
- Rechanneling flow paths to route uncaptured services to more potential users.

RESULTS

The SPAN model described above has been implemented as a core component of the NSF-funded “ARTificial Intelligence for Ecosystem Services” (ARIES) project’s software infrastructure. In this context, spatial environmental and economic datasets for model calibration and testing have been made available by case study partners in the Puget Sound (http://earth economics.org) and Madagascar (http://www.conservation.org). Discretization of the landscape was performed by converting all geographic data to a common resolution pixel-grid (raster) format. The location properties (Table 1) were described using Bayesian networks, which were initially designed based on literature reviews and were later vetted and extended by local experts in each case study area (Acknowledgments). These networks were applied to the feature data in each grid cell to provide discrete probability distributions for each location property. This approach was chosen in order to cope with data gaps in the available map measurements and to provide an intuitive means of expressing the uncertainty contained in the model results. Move and Decay functions, $\theta_{\text{trans}}$, and the property thresholds were also provided by experts associated with each project for each service under study.

Scenic Views

As a first example, we examine benefits provided by unimpeded views of natural landscapes (e.g., the economic value of views of mountains and water bodies as measured using hedonic analysis) (Bourassa, Hoesli, & Sun, 2004). In this case, the service medium is a measure of “scenic beauty” that is propagated by a movement function which follows lines of sight to potential beneficiaries. $\text{Source}_{\text{rel}}(v)$ assigns each grid cell $v$ a qualitative beauty measure with respect to all other cells in the study area. $\text{Use}_{\text{rel}}(v)$ highlights potential users of this service (for example, property owners in a given development district). $\text{Disuse}_{\text{rel}}(v)$ is undefined and unused for this service. Finally, $\text{Sink}_{\text{rel}}(v)$ estimates the detrimental effect of landscape features whose presence along a line of sight may detract from the view quality (i.e., billboards, clearcuts, industrial development). $\text{Decay}(W, R) = 0.8 W R^{-2}$ so that the impact of a view drops off quadratically with distance, and $\theta_{\text{trans}}$ is set arbitrarily small enough to allow carrier propagation across the entire study area. Optionally, increasing $\theta_{\text{trans}}$ restricts smaller carriers from transmitting service and can be used as a filter for discovering which areas receive the most service from each provision region.

In the following diagrams (Figure 2 and Figure 3), the pre- and post-flow estimates of the source, sink, use and flow density values are shown for the landscape surrounding the city of Kent, WA in the US Puget Sound region. Note, in particular, that the possible source which is available to beneficiaries in Kent is much less (denoted by its lighter shading) than the
Theoretical source due to the visually detracting effects of commercial and industrial development around the city.

The dark area in the upper left of the first image is part of the Puget Sound and that in the lower right is the portion of Mount Rainier within the study area. These and the smaller water bodies and hills scattered across the map are detected as sources of scenic beauty by the Source\textsubscript{rel} function. The second image shows potential sink zones (here denoted by commercial, industrial, and transportation-related development). The final image depicts the potential beneficiaries of the scenic view service: residential properties within the city of Kent.

These three maps indicate the flow densities between provision and use regions (Figure 4). The darkness of each path indicates the usable quality of the scenic beauty as it radiates from

---

Figure 2. Pre-flow estimates of source, sink, and flow

Figure 3. Post flow estimates

Figure 4. Flow density maps
Table 2. SPAN descriptions for six ecosystem services

<table>
<thead>
<tr>
<th>Service</th>
<th>Scenic Views</th>
<th>Proximity to Open Space</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benefit Type</strong></td>
<td>Provisioning</td>
<td>Provisioning</td>
</tr>
<tr>
<td><strong>Medium</strong></td>
<td>Scenic Beauty</td>
<td>Open Space</td>
</tr>
<tr>
<td><strong>Units</strong></td>
<td>Relative</td>
<td>Relative</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>Viewshed</td>
<td>Walking Distance</td>
</tr>
<tr>
<td><strong>Movement</strong></td>
<td>Line of Sight (Ray Casting)</td>
<td>Walking Simulation</td>
</tr>
<tr>
<td><strong>Decay</strong></td>
<td>Quadratic</td>
<td>Gaussian</td>
</tr>
<tr>
<td><strong>Rival?</strong></td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Mountains &amp; Water Bodies</td>
<td>Open Spaces in Urban Areas</td>
</tr>
<tr>
<td><strong>Sink</strong></td>
<td>Visual Blight</td>
<td>Walking Obstructions (Highways &amp; Fences)</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Property Value</td>
<td>Property Value</td>
</tr>
<tr>
<td><strong>Disuse</strong></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Service</strong></td>
<td>Carbon Sequestration</td>
<td>Flood Mitigation</td>
</tr>
<tr>
<td><strong>Benefit Type</strong></td>
<td>Provisioning</td>
<td>Preventive</td>
</tr>
<tr>
<td><strong>Medium</strong></td>
<td>Absorption</td>
<td>Water (Runoff)</td>
</tr>
<tr>
<td><strong>Units</strong></td>
<td>Absolute</td>
<td>Absolute</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>Global</td>
<td>Watershed</td>
</tr>
<tr>
<td><strong>Movement</strong></td>
<td>Atmospheric Mixing</td>
<td>Hydrologic Flow</td>
</tr>
<tr>
<td><strong>Decay</strong></td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Rival?</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Sequestration &amp; Storage Capacity</td>
<td>Rainfall &amp; Snowmelt</td>
</tr>
<tr>
<td><strong>Sink</strong></td>
<td>0</td>
<td>Water Absorption by Soil and Vegetation</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Carbon Emissions</td>
<td>Minimum Water for Total Damage</td>
</tr>
<tr>
<td><strong>Disuse</strong></td>
<td>0</td>
<td>Minimum Water before Flood Damage Incurred</td>
</tr>
<tr>
<td><strong>Service</strong></td>
<td>Nutrient Cycling</td>
<td>Avoided Sedimentation/Deposition</td>
</tr>
<tr>
<td><strong>Benefit Type</strong></td>
<td>Provisioning</td>
<td>Preventive</td>
</tr>
<tr>
<td><strong>Medium</strong></td>
<td>Nutrients in Water</td>
<td>Sediment</td>
</tr>
<tr>
<td><strong>Units</strong></td>
<td>Absolute</td>
<td>Absolute</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>Watershed</td>
<td>Watershed</td>
</tr>
<tr>
<td><strong>Movement</strong></td>
<td>Hydrologic Flow</td>
<td>Hydrologic Flow</td>
</tr>
<tr>
<td><strong>Decay</strong></td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Rival?</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Landscapes along Waterways</td>
<td>Landscapes along Waterways</td>
</tr>
<tr>
<td><strong>Sink</strong></td>
<td>Filters in Waterways</td>
<td>Riparian Zones</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Determined by Nutrient</td>
<td>Determined by Beneficiary</td>
</tr>
<tr>
<td><strong>Disuse</strong></td>
<td>Determined by Nutrient</td>
<td>Determined by Beneficiary</td>
</tr>
</tbody>
</table>
its point of origin toward the properties in Kent. The first shows all possible lines of sight along which the service medium may travel. The second depicts those flows which are blocked due to landscape sinks (i.e., visual blight). The last shows the actual view quality when sink effects are taken into account.

In contrast with the theoretical pre-flow projections, the post-flow source and sink values are significantly lower across the study area, demonstrating the utility of flow information in filtering out those regions which do, in fact, participate in the transfer of benefits. The first image shows the degree to which each source region is actually visible from the properties within Kent due to the landscape's topography. The actual sink image identifies the subset of the theoretical sink regions which are actually in the view path between any source and use location. Should improved views be desired, this result identifies those areas wherein reduction of the sink strengths will be most effective. The final map shows the relative view quality at each use location. Its similarity to the theoretical use map indicates that most, if not all, of the use regions do have sight paths to some of the aesthetically beautiful source regions. However, since sink effects on flow quality are not taken into account in these maps, the reader should be aware that the substantial amount of visual blight will have a significant impact on reducing these values in the actual source and use maps.

**DISCUSSION**

We have described in this paper the structure and operation of the SPAN model for quantitative ecosystem service assessment and have provided a sample of the kinds of novel results calculable using this approach. By adopting a discrete representation of the landscape as a collection of source, sink, and use regions which map to an abstract flow network, this framework can draw on a wide range of data aggregation techniques to match the scale of the assessment to the flow characteristics of the service being studied. Because service medium weights and the sink and rival use effects on them may be represented probabilistically, uncertainty about the strength of these service flows can be made explicit in the simulation results. The model’s benefit-centric focus on measuring flows of services from ecosystems to human beneficiaries enables more accurate value estimates than environmental simulations alone can provide. The provision and usage relationships between specific regions are clearly identified as well as the detrimental effects on service flows of both landscape features and human consumption. In instances in which different beneficiary groups compete for a finite resource, the flow paths clarify which groups have the earliest and/or easiest access. In cases of preventive services, the SPAN’s multi-stage flow calculations make it possible to estimate how much flow (which represents potential threats) each sink region blocks from reaching each use region. Finally and perhaps most interestingly, discovering and mapping the flow densities for particular services opens the door to an entirely new approach to managing landscapes for ecosystem services. Rather than planning just to protect ecosystems which appear to provide services, ES science can begin to support more holistic development or conservation plans that account for the service providers, their sink regions, and the flow corridors crucial to the transmission of these benefits to human users.

**Generalizability of the Model**

Having addressed both the model’s potential for scalability, communicating uncertainty, and generating new results provided by its flow-based, benefit-centric approach to ecosystem services, the last element to discuss is its generalizability across services. Due to page limitations, only one service was described in detail in the Results section. To provide a wider range of examples, Table 2 maps a number of ecosystem services into the SPAN formalism. Although only a subset of the commonly described services (Millennium Ecosystem Assessment (MA), 2005), we believe these are sufficiently representative of the larger list as to enable the creation of mappings for...
other services. The examples shown vary in the type of benefit provided (provisioning or preventive), rivalry of the resource, units of representation (relative or absolute), scale of effect, and movement function.

Open Problems and Next Steps

To conclude, we provide a short list of problems still to be addressed in order to improve the SPAN model’s scalability, generalizability, and applicability to decision processes as well as to continue extending the frontiers in quantitative ecosystem service assessment.

First, upper limits on downsampling spatial datasets must be determined for each service flow type, below which total reconstruction of the flow path can be accurately determined. This problem is related to the Nyquist-Shannon sampling theorem and the aliasing problem (Shannon, 1949). Second, identifying methods for traversing a polygonal mesh while maintaining global path constraints (such as line of sight adherence) is needed to ensure robust performance across multiple spatial scales. Third, extending the SPAN formalism to operate over graphs with cycles will enable the assessment of new services such as those related with tidal or marine systems. Fourth, making movement functions non-deterministic will allow the modeling of unpredictable service media such as storms or wildfires. Fifth, investigating flow path substitutability will add further detail to maps of critical flow regions by making irreplaceable flow corridors more valuable than others. Finally, the SPAN model can be used as a basis for spatial optimization techniques concerned with finding landscape configurations which maximize ES flow given cost (or other) constraints on spatial development activities.

ACKNOWLEDGMENTS

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REFERENCES


ENDNOTES

1 This definition of the term provisioning services differs from that given in the Millennium Assessment, in which it is used to mean physical goods obtained from Ecosystems (Millennium Ecosystem Assessment (MA), 2005).

2 A rival good is one whose use or consumption by one party leaves less available for use or consumption by others (Samuelson, 1954). Most physical goods and commodities bought and sold in the market are rival goods. A non-rival good is one that can be used by multiple parties without leaving less available for others. Examples include public safety, information in the public domain, and most regulating and cultural values provided by ecosystems.

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